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November 16, 1996

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Dear Major Kroll: 

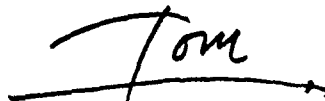
Enclosed please find a copy of the Final Report for AFOSR Grant Number :
AFOSR-93-1-0287 entitled:

"Frontier Geoplasma Research."

Please accept my apologies for the delay in submitting this report.

With kindest regards, I am

Yours Sincerely,



Tom Chang, Director

Enclosure

CC: Ms. Marilyn J. McKee
Chief, Contracts/Administrative Division, AFOSR/PKA
Mr. A. Favaloro, MIT/OSP
Mr. J. Politano, MIT/CSR

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describing the research of the

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performed under Grant AFOSR-93-1-0287 from the
Air Force Office of Scientific Research in support of
the Program entitled

FRONTIER GEOPLASMA RESEARCH

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Submitted by the
Center for Geoplasma Physics
Massachusetts Institute of Technology

Tom T.S. Chang
Director and Principal Investigator

November 16, 1996

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I. ABSTRACT

The Center for Theoretical Geoplasma Physics was established at MIT through an AFOSR University Research Initiative grant. The goal of the Center since its inception has been to develop and maintain a program of excellence in interdisciplinary geoplasma research involving the mutual interaction of ionospheric scientists, aeronomists, plasma physicists and numerical analysts. During the past three years under the current research Grant "Frontier Geoplasma Research", members of the center have made seminal contributions to a number of definitive research findings in the fundamental understanding of the polar wind, the black auroral curls, ionospheric turbulence, particle acceleration, and the phenomenon of coupling between the ionosphere and magnetosphere. Some of the results of these research activities have already found practical applications toward the mission of the Air Force by scientists at the Geophysics Directorate of the Phillips Laboratory, particularly those affiliated with the research group headed by Dr. J. R. Jasperse of the Ionospheric Effects Branch.

Our MIT Center is now recognized world-wide as a star example of a successful enterprise between a prestigious educational institution and an established governmental research laboratory, the Phillips Laboratory. We are now receiving partial funding from AFOSR, NASA and NSF that will allow the Center to continue its now well-established research programs, and to develop other new frontier research projects. MIT has sponsored an annual symposium series on the "Physics of Space Plasmas" and a workshop series on "Theoretical Geoplasma Physics". It has also participated, with the Graduate School of MIT, in a Minority Summer Research Program, to effect changes in the realm of graduate scientific training for minorities. All of these activities have received considerable praise and support from the world-wide scientific community.

II. INTRODUCTION

For the United States Air Force to enjoy its continuing success in meeting the demands of its mission heading into the 21st century, it must be prepared to operate in the "New Frontier" of space, particularly its every-changing turbulent geoplasma environment. Recognizing this importance, a Center of Excellence in Theoretical Geoplasma Research was established at the Massachusetts Institute of Technology under the sponsorship of the Air Force Office of Scientific Research.

During the past three years, we have succeeded in developing the basic understanding of several microscale/mesoscale geoplasma phenomena of considerable importance. These include the study of the origin of high-latitude ionospheric turbulence, the nonlinear development of the highly anisotropic photoelectron driven polar wind, the generation of intense divergent electric fields and the phenomenon of black auroral curls, the pitch-angle scattering phenomenon produced by precipitating electrons, the formation of ion conics in the auroral and cusp regions, the formation of counterstreaming electrons along auroral field lines, the onset of double layers and electron acceleration in the boundary plasma sheet, the fundamental kinetic process leading to the anomalous heat transfer in ionospheric transport, and other related nonlinear and turbulent terrestrial plasma processes such as intermittent, localized magnetic reconnection. Together, we have published *26 joint technical papers* and *4 books*, and delivered *43 invited and review lectures* at various international conferences and renowned institutions.

A number of the afore-mentioned research findings have already found practical applications by our colleagues at the Geophysics Directorate of the Phillips Laboratory. Examples of such applications are: prediction of charged-particle precipitation patterns and deposition profiles in the diffuse-auroral zone of

the ionosphere; prediction of solar EUV and X-ray fluxes based on ionospheric photoelectron measurements and transport calculations; and calculation of ionospheric electron density profiles in the mid-latitude, high-latitude and polar regions of the globe.

Our Center and the Geophysics Directorate (led by Drs. Tom Chang at MIT and J.R. Jasperse at GL) jointly sponsored a series of Symposia on the "Physics of Space Plasmas". The principal purpose of these symposia is to provide an annual get-together for space scientists from the various research groups in the Boston-New England area. It has since attracted contributions from scientists world-wide. Each symposium included the presentation of an "Alfvén Lecture" established in honor of the Nobel Laureate, Professor Hannes Alfvén of the Swedish Royal Institute of Technology. Alfvén Lecturers have included such luminaries as Professor Oscar Buneman of Stanford University, Professor Jim Dungey of the Imperial College, London, Professor Eugene Parker of the University of Chicago, Dr. Roger Gendrin of the French National Laboratory of Ionospheric and Magnetospheric Physics, Professor Charles Kennel of UCLA and an Associate Administrator of NASA, and Professor Alfvén himself.

Jointly, we also organized a series of Cambridge Workshops in Geoplasma Research. Each workshop is targeted at a specific topic of frontier geoplasma research and includes basic tutorial talks and invited specialty lectures. The format of the workshops has been designed to allow ample discussion time and interactions. These activities have received much praise from the world-wide geoplasma community for their innovative concepts and educational merits. Proceedings of the symposia and workshops entitled, "Physics of Space Plasmas" have become informal textbooks treasured by both established scientists and students in geoplasmas.

Our Center has interacted actively with a number of research organizations in addition to the Geophysics Directorate/Phillips Laboratory. These include the Naval Research Laboratory, Cornell University, the Universities of California at Berkeley, Los Angeles and Irvine, the University of Maryland, the University of New Hampshire, Dartmouth College, Boston College, the Max-Planck Institutes for Extraterrestrial Physics and of Aeronomy, the Utah State University, the Lockheed Palo Alto Research Laboratory, the National Research Council of Canada, and the Imperial College of London. Visits to these institutions and by scientists from these institutions have provided the necessary stimulus to keep our research program vibrant, up-to-date, and at the same time constantly in touch with practical motivations.

One of the prime missions of the MIT Center for Theoretical Geo/Cosmo Plasma Physics is to provide an environment for the development of young prospective students in space plasma education. During the past three years, in cooperation with the MIT Graduate School and the MIT Minority Summer Research Program (MSRP), the MIT Center hosted a number of talented young minority and female undergraduate interns. By intermingling with the established scientists at the Center, these young interns obtained first hand knowledge of the true meaning of scientific research in ionospheric physics.

The Center is currently composed of 18 participating members. These include members of the faculty, staff, postdoctoral and graduate students at MIT as well as visiting scientists from other interacting institutions. Members of our Center have constantly been invited by various conferences, universities, and other organizations to deliver invited and review articles. In addition, the Center pursues a vigorous visiting scientists program which has attracted many renowned scientists to the MIT campus.

The Center has a modern computing environment served locally by an inter-connecting group of workstations and externally by the Pittsburgh Supercomputer Center.

The report is organized as follows. In Sec. III, we discuss the progress and accomplishments of our Center during the grant period. This is followed by a list of selected scientific publications in Sec. IV. A complete list of invited and review talks by the Center personnel during this period is provided in Sec. V.

III. PROGRESS AND ACCOMPLISHMENTS

In our original AFOSR URI proposal, we proposed a unique program of theoretical research in geoplasma physics. The Center would be a single cohesive unit of scientists from several disciplines interacting effectively with one another and with groups from external ongoing experimental research programs. It would not be the purpose of the Center to carry out routine data analyses. Instead, our approach would be to interact with the experimental groups and to identify from the analyzed data those problems that had no ready-made explanations and to focus our efforts on the solution of such new problems. At all times, we would not lose sight of the practical applications of the developed theories to the prime mission of the Air Force.

During the past three years under the current program "Frontier Geoplasma Research", we have endeavored to follow such guidelines while developing the various research efforts at the Center. We identified many new, interesting, and at the same time puzzling geoplasma problems that were not admissible to "routine" solutions. We have provided theoretical understanding to a number of such identified problems. In many of these instances, we were able to provide quantitative descriptions of the phenomena or make useful theoretical predictions for future observations and applications.

The most exciting research findings of our group during this period included the development of an "Intermittent Turbulence Theory" of magnetic reconnection that is germane to the coupling process between the ionosphere and magnetosphere in the auroral region and the continued development of a novel theory of the polar wind based on the anomalous heat transport of the photoelectrons in the dayside polar ionosphere. Other important research activities included: the study of infrared emissions during upward propagating lightning

strokes, the multi-dimensional aspects of the black auroral curls, the development and propagation of electromagnetic ion cyclotron waves throughout the terrestrial ionosphere, and the nonlinear phenomena of electron and ion acceleration in the high-latitude ionosphere.

A number of our research findings have recently been confirmed by the experimental data collected by high-time resolution instruments on board the "POLAR" and "AKEBONO" satellites as well as the TOPAZ, SCIFER and AMICIST high-altitude rockets. As it has been the history of all past research activities of the MIT Center, our recent work is directly related to AF C³I systems. The coupling phenomenon between the Earth's ionosphere and magnetosphere, intermittent MHD turbulence, the polar wind outflow, the black auroral curls, and ionospheric lower hybrid cavitary structures all have profound effects on the high-latitude electron and ion density profiles as well as signal and wave propagations. The understanding of these phenomena is germane to space surveillance, space launch and orbit operations, as well as space weather modeling and forecasting. In particular, our understanding of pitch-angle scattering and the dynamics of the central plasma sheet allowed us to construct a quantitative model of electron precipitation in the diffuse aurora. Because this precipitation helps control the electron density profile in the high-latitude ionosphere, it has a strong impact on the Air Force communication and surveillance systems that must operate in the region. Similarly, because of the effect of scintillation on these systems and the close relationship between scintillations and the high-latitude ionospheric turbulence, our quantitative models of the latter phenomena and its consequences can be expected to have great utility in the practical business of ionospheric weather prediction.

Listed below are research topics that have been studied and analyzed by the members of the center personnel during the grant period.

- Nonlinear vortex description of black auroral curls.
- Sporadic, localized magnetic reconnection and intermittent turbulence in the ionosphere-magnetosphere coupling region.
- Anisotropic, kinetic polar wind driven by the dayside-photoelectrons.
- Upward propagating intense lightning strokes and associated infrared emissions in the lower ionosphere.
- Ion heating by low frequency waves in Earth's ionosphere and magnetosphere.
- Lower hybrid collapse, caviton turbulence, and charged particle energization in the topside ionosphere.
- Mode conversion processes involving the plasma turbulence of oxygen-hydrogen plasmas in the magnetosphere and ionosphere.
- Turbulent relaxation of magnetic fields in space plasmas.
- Path integral approach to nonlinear particle acceleration and diffusion in ionospheric plasmas.
- Ion and electron acceleration along auroral field lines.
- Nonlocal effects of finite beam-driven instabilities in space plasmas.
- Convection of ion cyclotron waves to ion heating regions.
- Decay of ion beam driven acoustic waves into ion holes and double layers along auroral field lines.
- Broad band spectrum of auroral plasma turbulence.

- Renormalization-group calculation of self-organized criticality and low-dimensional behavior of auroral substorm onsets.
- Theory of nonlinear electric fields in the auroral acceleration region.
- Stochastic MHD models for space plasmas.
- Multiple-cyclotron absorption of ion heating in the cusp/cleft region.
- Wave-particle ion cyclotron turbulence and evolution of the electron distribution in inhomogeneous space plasmas.
- ULF waves along auroral field lines in the central plasma sheet.
- Energy source and generation mechanism for auroral kilometric radiation.
- Trapped electrons as free energy source for the auroral kilometric radiation.
- Particle acceleration by intense auroral VLF waves.
- The electron beam instability and turbulence theories in space plasmas.
- Two stream interaction on auroral field lines.
- Energetic photoelectron and the polar rain.
- Monte-Carlo modeling of polar wind electron distributions with anomalous heat flux.
- Counterstreaming electrons generated by lower hybrid waves in the auroral region.
- Heating of thermal ions near the equatorward boundary of the mid-altitude polar cusp.
- Stabilization of the cyclotron autoresonance maser instability in space plasmas.
- Nonlinear oblique whistler modes in collisionless shocks of space plasmas.
- Electromagnetic tornadoes in space.

- Radiations from large space structures in low Earth orbit with induced AC currents.
- Ion waves and upgoing ion beams observed by the VIKING satellite.
- Simulation of ion conic formation in the ionosphere and magnetosphere.
- Alfvén engine in space.
- Convection of ion cyclotron waves to ion heating regions in the auroral zone.
- Wave observations and their relation to nonresonant and resonant particle heating processes.

Since the details of these research programs have been fully documented in our annual reports and published archival scientific articles, they will not be repeated here. Instead, we include in this report two detailed lists of scientific publications and invited lectures by all the members of our Center during the grant period. These lists demonstrate the diversity and breadth of the accomplished research programs at the Center and provide a good indicator of how well these research results are received by our peers.

IV. SELECTED RECENT PUBLICATIONS:

- Abe, T., B. Whalen, A.W. Yau, E. Sagawa, and S. Watanabe, Akebono observations of thermal ion outflow and electron temperature in the polar wind region, *Physics of Space Plasmas*, 13, 3, 1996.
- André, M. and Tom Chang, Ion heating perpendicular to the magnetic field, *Physics of Space Plasmas*, 12, 35, 1993.
- André, M., P. Norqvist, A. Vaivads, L. Eliasson, O. Norberg, A. Eriksson and B. Holback, Transverse ion energization and wave emissions observed by the Freja Satellite, *Geophys. Res. Lett.*, 21, 1915, 1994.
- Basu, B., J.R. Jasperse, J.M. Retterer, D.T. Decker, and Tom Chang., Theory and observations of high frequency electrostatic plasma instabilities in the lower ionosphere, *Physics of Space Plasmas*, 12, 147, 1993.
- Chang, Tom, Lower hybrid collapse, caviton turbulence, and charged particle energization in the topside auroral ionosphere and magnetosphere, *Physics of Fluids*, B5, 2646, 1993.
- Chang, Tom, and M. André, Ion heating by low frequency waves, in *Auroral Plasma Dynamics*, edited by R.L. Lysak, AGU Monograph No. 80, 207 (American Geophysical Union, Washington, D.C., 1993.)
- Chang, Tom, Low-dimensional behavior and symmetry breaking of stochastic systems near criticality-Can these effects be observed in space and in the laboratory?, *IEEE Trans. on Plasma Science*, 29(6), 691, 1992.
- Chang, Tom, Path integrals, differential renormalization-group and stochastic systems in space near criticality, *Intern. J. Engr. Science*, 30(10), 1401 1992.
- Chang, Tom, Path integral approach to stochastic systems near self-organized criticality, in Recent Trends in Physics, *Nonlinear Space Plasma Physics*, edited by R. Sagdeev et al., American Institute of Physics, NY, 252, 1993.
- Dum, C.T., Lower hybrid wave-particle interaction and auroral acceleration, *Physics of Space Plasmas*, 13, 155, 1996.
- Dum, C.T., Weak and strong turbulence theory, *Physics of Space Plasmas*, 13, 75, 1995.
- Dum, C.T., and K.-I. Nishikawa, Two-dimensional simulation studies of the electron beam-plasma instability, *Physics of Plasmas*, 1, 1821, 1994.
- Ganguli, S.B., Tom Chang, F. Yasseen, and J.M. Retterer, Plasma transport Modeling using a combined kinetic and fluid approach, *Physics of Space Plasmas*, 12, 393 1993.

- Jasperse, J.R., B. Basu, J.M. Retterer, D. Decker, and Tom Chang, High frequency electrostatic plasma instabilities and turbulence layers in the lower ionosphere, in *Space plasmas: coupling between small and medium scale processes*, edited by M. Ashour-Abdalla, Tom Chang, and P. Dusenbery, *AGU Monograph No. 86*, 77, 1994.
- Johnson, J.R., Tom Chang and G.B. Crew, A study of mode conversion in an oxygen-hydrogen plasma, *Physics of Plasmas*, 2, 1274, 1995.
- Johnson, J.R., and Tom Chang, Nonlinear vortex structures with diverging electric fields and their relation to the black aurora, *Geophys. Res. Lett.*, 22, 1481, 1995.
- Johnson, J.R., and C.Z. Chang, Global mirror modes in the magnetosheath, *Physics of Space Plasmas*, 13, 361, 1996.
- Retterer, J.M., Tom Chang and J.R. Jasperse, Transversely accelerated ions in the topside ionosphere, *J. Geophys. Res.*, 99, 13189, 1994.
- Retterer, J.R., J.M., Tom Chang and J.R. Jasperse, Lower hybrid collapse and charged particle acceleration, in Recent Trends in Physics, *Nonlinear Space Plasma Physics*, edited by R. Sagdeev et al., American Institute of Physics, NY, 252, 1993.
- Tam, Sunny W.Y. and Tom Chang, The limitation and applicability of Musher-Sturman equation to two-dimensional lower hybrid wave collapse, *Geophys. Res. Lett.*, 22, 1125, 1995.
- Tam, Sunny W.Y., F. Yasseen, Tom Chang, and S. Ganguli, Self-Consistent Kinetic Photoelectron Effects on the Polar Wind, *Geophys. Res. Lett.*, 22, 2107, 1995.
- Tam, W.Y., F. Yasseen, Tom Chang, and S. Ganguli, Photoelectron effects in the polar wind, *Physics of Space Plasmas*, 13, 619, 1996.
- Tam, S.W.Y., F. Yasseen, Tom Chang, S.B. Ganguli, and J.M. Retterer, Anisotropic kinetic effects of photoelectrons on polar wind transport, in *Cross-scale Coupling Processes in Space Plasmas*, edited by J. Horwitz et al., *AGU Monograph No. 93*, 133, 1995.
- Tetreault, D., Turbulent relaxation of magnetic fields: 1. Coarse-grained dissipation and reconnection, *Physics of Fluids*, 97, 8531, 1992.
- Tetreault, D., Turbulent relaxation of magnetic fields: 2. Self-organization and intermittency, 97, 8541, 1992.

- Yau, A.W., T. Abe, Tom Chang, T. Mukai, K.I. Oyama, and B.A. Whalen, Akebono observations of electron temperature anisotropy in the polar wind, *J. Geophys. Res.*, 100, 17451, 1995.

BOOKS

- "Space Plasmas: *Coupling between Small and Medium Scale Processes*," AGU Geographical Monograph No. 86, edited by M. Ashour-Abdalla, Tom Chang and P. Dusenbery, (American Geophysical Union, Washington, D.C., 1995).
- "Physics of Space Plasmas: *Controversial Issues and New Frontier Research in Geoplasmas*," Volume 12, edited by Tom Chang and J.R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA 1993).
- "Physics of Space Plasmas: *Chaos, Stochasticity, and Strong Turbulence*," Volume 13, edited by Tom Chang and J.R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA 1995).
- "Physics of Space Plasmas: *Multi-Scale Phenomena in Space Plasmas*," Volume 14, edited by Tom Chang and J.R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA 1996).

V. INVITED LECTURES

During the grant period, we delivered a total of forty three (43) invited and review lectures at various national and international conferences and research institutions on topics related to: particle acceleration mechanisms in space, auroral phenomena, self-organized criticality, magnetic substorms, chaos and stochasticity, renormalization group, magnetic reconnection, and the polar wind.

- Western Pacific Geophysics Meeting, Brisbane, Australia, July 1996.
- Huntsville Workshop: Encounter between Global Observations and Models in the ISTP Era, Guntersville, AL, September 1996.
- General Assembly of the International Union on Radio Science, Lille, France, August 1996.
- Chapman Conference on the Magnetotail: New Perspectives, Kanazawa, Japan, November 1996.
- Collective Processes in Nonlinear Media, Trieste, Italy, October 1995.
- Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, May 1995.
- Workshop/Symposium on Multiscale Phenomena in Space Plasmas, Bermuda, February 1995. (2 lectures.)
- International Symposium on Space Sciences, Taiwan, November 1994.
- Workshop on Coupling of Micro- and Mesoscale Processes in Space Plasma Transport, Guntersville, AL, October 1994. (2 lectures.)
- Western Pacific Geophysics Meeting, Hong Kong, July 1994. (2 lectures.)
- International Conference on Nonlinear Waves and Chaos in Space Plasmas, Kyoto, Japan, June 1994.
- Second International Conference on Magnetic Substorms, Fairbanks, Alaska, March 1994.
- Fall Meeting of the American Geophysical Union, San Francisco, CA, December 1993. (2 lectures.)
- International Conference on Research Trends in Plasma Astrophysics, La Jolla, CA, November 1993.
- Royal Institute of Technology, Stockholm, Sweden, October 1993.
- Swedish Space Research Institute, Kiruna, Sweden, September 1993.
- Swedish Space Research Institute, Uppsala, Sweden, September 1993

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- Swedish Space Research Institute and the University of Umeå, Umeå, Sweden, September 1993
 - International Beacon Satellite Symposium, Cambridge, MA, July 1993.
 - International School on Space Plasmas, Volga River, Russia, June 1993. (2 lectures.)
 - Space Research Institute, Moscow, Russia, June 1993.
 - Yosemite Meeting on Solar Systems, Yosemite, CA, February 1993.
 - Space Science Center, University of New Hampshire, Durham, N.H., February 1993.
 - Spring Meeting of the American Geophysical Union, Baltimore, MD, May 1993.
 - Second International Workshop on the Interrelationship Between Plasma Experiments in the Laboratory and in Space, Banff, Canada, June 1993.
 - Spring Meeting of the American Geophysical Union, Baltimore, MD, May 1993.
 - IEEE International Workshop on Plasma Cosmology and Astrophysics, Princeton, N.J., May 1993.
 - Space Sciences Laboratory, University of California, Berkeley, CA, April 1993.
 - STAR Laboratory, Stanford University, Palo Alto, CA, April 1993.
 - Yosemite Meeting on Solar Systems, Yosemite, CA, February 1993.
 - Fall Meeting of the American Geophysical Union, San Francisco, CA 1992.
 - American Physical Society, Plasma Physics Meeting, Seattle, WA, November 1992.
 - Third Huntsville Workshop on Magnetosphere/Ionosphere Plasma Models, Huntsville, AL, October 1992.
 - Western Pacific Geophysics Meeting, Hong Kong, August 1992. (2 lectures.)
 - Cambridge Workshop on Space Plasmas, MIT, Cambridge, MA 1992.
 - Nineteenth IEEE International Conference on Plasma Science, Tampa, FL, June 1992.
 - Chapman Conference on Micro/Meso Scale Phenomena in Space Plasmas, Kauai, Hawaii, February 1992. (3 lectures.)